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Mapping Forest Growth and Degradation Stage in the Brigalow Belt Bioregion of Australia through Integration of ALOS PALSAR and Landsat-derived Foliage Projective Cover (FPC) Data.

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Abstract

Focusing on 12 Regional Ecosystems (REs) distributed across the Brigalow Belt Bioregion (BRB) of Queensland, Australia, where brigalow (*Acacia harpophylla*) dominated the plant communities, this study aimed to discriminate and map different forest growth/degradation stages using a combination of Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) L-band HH and HV polarisation data and Foliage Projective Cover (FPC) derived from time-series of Landsat sensor data acquired over a single year. Previously, the Queensland Herbarium had mapped brigalow-dominated remnant forests within each RE, with these considered to be structurally mature and undisturbed by direct human activity, at least since the 1940s to 1950s. From these remnant areas, frequency distributions of all three channels were extracted and compared to those of image segments, generated from FPC and PALSAR data. Outside of the remnant area and within areas supporting woody vegetation (mapped using an FPC threshold of ≥ 9 %), mature non-remnant forests were associated with segments where the HH and HV backscatter thresholds were within one standard deviation of the mean extracted for remnant forest. Early-stage regrowth was then differentiated using a L-band HH threshold of < -14 dB, common for all REs because of similarities in structure at this stage. The early-stage included forests regrowing over several decades and often occurred in areas recovering from recent clearing events. Regardless of the RE, this stage was typified by a high density of stems (often exceeding 10,000 ha^{-1}) of low stature (< 2-3 m in height) and canopy cover up to ~ 50 %. Objects falling between the early and mature stages were considered to be intermediate regrowth and/or degraded forest. All areas with an FPC < 9 % were mapped as non-forest.

Within the BRB, forests with brigalow REs as a dominant or subdominant component originally occupied over 7.3 million ha but were reduced to 586,364 ha of remnant forest by 2009, with 460,499 ha (78.5 %) having brigalow as the dominant component. Using the Landsat FPC and ALOS PALSAR data, an additional 722,686 ha of brigalow-dominated regrowth forest were identified giving a total forested area (brigalow-dominated remnant and secondary forest) of 1,183,185 ha or 17.2 % of the area of the 12 REs. Within this area, 368,473 ha (31.1 %) were mapped as early regrowth in areas recovering from recent clearance events and 230,551 (19.5 %) ha and 123,662 ha (10.5 %) as intermediate and mature (non-remnant) stages respectively with the remainder (38.9 %) being remnant forest. Users' and producers' accuracies were, respectively, 81 % and 69 % for early regrowth and 71 % and 89 % for mature and intermediate stage forests combined. The mapping provided a structural, rather than an age-based classification of growth stage, typically associated with regrowth mapping using time-series comparison of optical imagery. The regional estimates of growth/degradation stage generated for the BRB can advise management strategies aiming to optimise the use and recovery of these threatened brigalow ecosystems with benefits for biodiversity and carbon sequestration.

Keywords: Brigalow, ALOS PALSAR, Landsat, regrowth, degradation, carbon, biodiversity

1 Introduction

The clearance of forests across the world has contributed to significant declines in both terrestrial carbon stocks and habitat, leading to increased levels of atmospheric greenhouse gases and losses of biodiversity (including species extinctions; Dirzo and Raven, 2003; Pan *et al*., 2011). Nevertheless, in many regions, forests are regenerating on abandoned and/or previously disturbed land, providing potential for the restoration of ecosystem structure, diversity and function (Ramankutty and Foley, 1999; Bowen *et al*., 2007; 2009). Primary forests that have remained intact (often referred to as remnant) also contain substantial stocks of carbon (Gibbs *et al*., 2007) and a high diversity of plant and animal species (Barlow *et al*., 2007). Efforts focusing on conserving forest ecosystems for biodiversity and carbon values therefore rely on knowledge of the extent of remnant forest (which need to be conserved) and secondary forests at different stages of growth and degradation (which need to be protected and managed to facilitate ecosystem restoration and provide additional carbon sequestration). Spatial and quantitative information on forest extent, structural attributes (e.g., cover, height) and biomass, and changes in these is also critical for advising management strategies that aim to optimise the recovery of forest ecosystems to retain biodiversity and enhance terrestrial carbon stocks. However, for many regions of the world, such information is lacking. For this reason, increasing emphasis is being placed upon using remote sensing observations to fill these gaps, particularly as these forests are often scattered over vast areas and may be experiencing rapid change (Chambers *et al*., 2007; Goetz *et al*., 2009).

A common approach to mapping the growth stage of forests has been to use time-series of remote sensing (primarily optical) data to differentiate forests of differing age (e.g., Yanesse *et al*., 1997; Prates-Clark *et al.,* 2009; Helmer *et al*., 2009). These methods are data intensive and assume stand age to be an indicator of the stage of development relative to that of the primary or mature forest, with older forests often considered the most similar in terms of structure and species composition (Bowen *et al.,* 2007). However, the succession of forests may be influenced by a number of factors, such as clearing mechanisms, periods and types of use, the history of burning as well as physical factors such as soils, climate and topography (Prates-Clark *et al.,* 2009). Degradation of forests within the same landscape, including those that are regenerating, is also not considered, with many forests assumed to be developing in one direction. For these reasons, forests of the same age may differ in their structure, species composition and biomass and rates of change in these attributes over time (Lucas *et al.,* 2002). Whist age information is important to retain, remote sensing efforts also need to be directed towards tracking the structural development or degradation of forests relative to the mature state and ideally quantifying the changes in biomass (carbon) over time. Such an approach is also advantageous as structure often relates to the way that fauna are distributed within and utilise a habitat (Bowen *et al*., 2007; Selwood *et al.,* 2009).

Using areas within the Brigalow Belt Bioregion (BRB) in Queensland, Australia, as an example, Lucas *et al*. (2006) proposed an approach to identifying regenerating forests at the earliest stage of structural development that combined single-date NASA JPL airborne Synthetic Aperture Radar (AIRSAR) L-band HH (~25 cm wavelength) polarisation data and Landsat-derived Foliage Projective Cover (FPC). FPC is the percentage of an area occupied by the vertical projection of foliage, and is estimated routinely for the state of Queensland using a multiple regression relationship established between field measures of woody FPC and Landsat sensor visible (green and red), near infrared and shortwave infrared data. The FPC of woody vegetation is determined by accumulating measures of FPC retrieved from time-series of Landsat sensor data, which disaggregates the seasonal contribution from herbaceous vegetation (Armston *et al*., 2009). The accuracy of retrieval was increased when Vapour Pressure Deficit (VPD), defined as the difference in vapour pressure from a saturated atmosphere, was included in the regression because of the known correspondence between the evaporative potential of the atmosphere and FPC (Specht and Specht, 1999). Based on cross-validation comparisons (Armston *et al.,* 2009), the regression model provided an adjusted R^2 of 0.80 and RMSE of < 10.0 % for the estimation of FPC. Lucas *et al*. (2006) identified the early-stage of regeneration as areas supported an FPC associated with forests but an L-band HH backscattering coefficient more typical to non-forest. Clewley *et al*. (2012) expanded this approach to differentiate early-stage from more intermediate and mature stages by referencing the characteristics of remnant forest, although instead used Japanese Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) HH and HV with Landsat-derived FPC data to facilitate regional applications. This study therefore sought to evaluate whether the methods of Lucas *et al*. (2006) and Clewley *et al*. (2012) could be used in combination to differentiate forests at progressive stages of structural development and/or degradation across the BRB given the diversity of ecosystems, environments and climates occurring, with focus on ecosystems dominated primarily by brigalow (*Acacia harpophylla*). By generating new maps of forest growth and/or degradation stage for the BRB, significant capacity to quantify biodiversity and carbon stocks and dynamics would be provided as well as knowledge on where future restoration activities might be targeted.

In Queensland, Regional Ecosystems (REs) are defined as vegetation communities that are associated with a particular combination of geology, landform and soil (Sattler and Williams, 1999). The extent of these REs, whether currently forested or otherwise, has been mapped through reference to the physical environment and consistent patterns detectable within time-series of aerial photography and satellite imagery over the whole region, with these supported by a limited number of known sample points to provide a description (Neldner et al., 2012). As few images are available across Queensland before the early 1960s and few sample points exist before the 1970s (apart from localised explorer and early settle records), what is often referred to as the pre-1750 or pre-European extent of the REs (i.e., prior to major impacts from non-indigenous populations) is difficult to ascertain, particularly as ecosystem boundaries might also have changed. Hence, the pre-clearing extent is defined, with this referring to REs present before known clearing (if occurring) but equating generally to the 'pre-1750' or 'pre-European extent (Neldner *et al*., 2005; 2012; Accad *et al*., 2008; 2012). In some cases, old survey records (e.g., from the 1940s and 1950s) have been used to determine the pre-clearing vegetation in areas already cleared (Fensham and Fairfax, 1997). Remnant forests are considered to be those that have remained intact before and throughout this period and have never been cleared. In many cases though, the earliest period where these forest were observed is the 1940s and 1950s when aerial photographs were first acquired.

This study focused particularly on 12 REs within the BRB where brigalow is dominant within the forest community, although within the mapped areas, this species may be subdominant. All 12 REs considered are endangered following decades of clearing for agriculture, with ~ 8 % of the original area (where brigalow is either dominant or subdominant) remaining in remnant patches (as of 2009, Accad et al., 2012). Nevertheless, forests regenerated on many clearances and exist in various stages of regeneration as well as degradation. Those in the earliest stages of regrowth were, however, often recleared to maintain pastures (Fensham and Guymer, 2009). All regrowth forests, and particularly those in the earliest stage, have increasingly being recognised as providing a potential carbon sink with strong co-benefits for biodiversity and landscape health (Valbuena *et al.,* 2010). Hence, the generation of accurate maps of growth stage as well as degradation state for these ecosystems would contribute to efforts supporting restoration of their biodiversity values and increasing potential for carbon sequestration.

The paper is structured as follows. Section 2 provides important background information to the BRB relating to the physical environment and land use histories and briefly reviews previous research that has focused on mapping forest growth stages from remote sensing data. Section 3 then describes the ALOS PALSAR and Landsat FPC datasets used for classification, the Regional Ecosystem (RE) mapping (Queensland Herbarium, 2012c), field data and BioCondition reports (Eyre et al., 2011) for REs with brigalow as a dominant component. The procedures developed to map growth (including degradation) stages are described. In Section 4, the map of these stages and area estimates for the BRB of Queensland are provided together with estimates of classification accuracy. Section 5 discusses the approach and conveys the importance of the study in terms of environmental conservation and benefits to landholders. Section 6 concludes the study and recommends future research directions.

2 The Brigalow Belt Bioregion: status and vulnerability

2.1 Physical environment

The BRB is one of 13 bioregions in Queensland and covers an area of approximately 36.5 million ha that extends across the semi-arid tropical and subtropical regions of eastern Australia (Sattler and Williams, 1999; Figure 1a). Most of the bioregion is contained within Queensland but extends into northern New South Wales. Brigalow is dominant in 16 REs across Queensland, with 12 located within the BRB (Bioregion number 11; http://www.ehp.qld.gov.au/ecosystems/biodiversity/regional-ecosystems/index.php) and the remainder occur in the adjoining Mulga Lands (Bioregion 6) and Southeast Queensland Bioregions (Bioregion 12; Table 1). The BRB extends across a rainfall gradient, with over 1200 mm falling annually towards the coast decreasing to < 300 mm towards the interior (Figure 1b).

INSERT TABLE 1 HERE.

2.2 Vegetation

Whilst brigalow may be dominant or subdominant within forest communities, other species often occur alongside, including belah (*Casuarina cristata*) and *Eucalyptus* (Sattler and Williams, 1999; Table 1). The structure of forests is also variable within and between REs, depending on soils, topography, climate and disturbance regimes associated with fire, herbivory, grazing, and selective clearing and thinning. Based on classifications that use height and cover as structural descriptors (Specht and Specht, 1999), the vegetation is defined primarily as open forest (30-70 % cover, 10-30 m height), low open forest (5-10 m height) or woodland (10-30 % cover, 10-30 m height; Specht, 1970). The majority of brigalow ecosystems support either a shrub or low tree layer.

The relative differences in the structure of brigalow-dominated forests as they regenerate was highlighted by Accad *et al*. (2010) using field data acquired by Bowen *et al*. (2009) and Dwyer *et al*. (2010b) from several REs across the BRB and estimates of forest age determined through reference to time-series of remote sensing data and interviews with land holders. As forests regenerate over time following clearance, their basal area (as a function of stem diameter), height, cover and biomass increased (Figure 1). However, the canopy cover became similar for forests older than ~ 20 years, with some younger forests locally supporting a canopy cover > 40 % within 10 years. The density of stems for forests sampled and aged up to 10 years of age was up to 7000 stems ha^{-1} but approached 15,000 stems per ha^{-1} for forests aged 10-20 years, decreasing thereafter to < approximately 3000 stems per ha^{-1}.

INSERT FIGURE 1 HERE

INSERT FIGURE 2 HERE

2.3 History and consequences of vegetation clearing in the BRB

Of the 13 bioregions in Queensland, the BRB has experienced some of the highest rates of anthropogenic clearance. Clearing commenced around 1840 and was largely for pastoral (sheep and cattle production) but extended to cropping on the more fertile soils in the late 19th and 20th centuries (Fensham *et al*., 1998; Seabrook *et al*., 2006). As a consequence, 41.7 % of all vegetation (including communities where brigalow is dominant or subdominant) in the 36 subregions of the Queensland portion of the BRB was regarded as remnant in 2009, with less than 20 % remaining in 10 of these and the Tara Downs subregion having the lowest proportion of 6.3 % (Accad et al., 2012).

The 12 REs considered in this study originally covered an area of 7,318,750 ha. However, 90 % was cleared of woody vegetation prior to 1997 and the extent was further reduced to about 8 % by 2009, leaving 586,364 ha with 460,499 ha (78.5 %)

dominated by brigalow (Accad *et al*., 2012; Table 2). As a result of clearance, the brigalow is now the most threatened widespread vegetation type in Queensland (Johnson and McDonald, 2005), with several REs with brigalow occupying less than 10,000 ha. All 12 REs with brigalow as a major component within the BRB are considered endangered (Accad *et al*., 2008) and whilst some remnant forests are protected in conservation areas (e.g., national parks), many occur as fragmented blocks across a largely deforested landscape (Seabrook *et al*., 2007).

INSERT TABLE 2 HERE

2.4 Previous mapping of forest growth stages

For the majority of REs in Queensland, the remaining vegetation (herein referred to as remnant) has been mapped by the Queensland Herbarium using a combination of time-series aerial photography and satellite (primarily Landsat) sensor data, with the most recent mapping being for 2009 (Queensland Herbarium, 2012b). To support the mapping of all REs across the State, the Queensland Herbarium has established around 20,000 detailed and quaternary CORVEG (Neldner *et al*., 2005) field sites. In the field, forest ecosystems are considered as remnant only when they support a tree canopy with more than 70 % of the height and 50 % of the cover relative to stands of the same species composition in areas known to be undisturbed (i.e., those showing no evidence of extensive mechanical or chemical disturbance; Neldner *et al*., 2005).

Regrowth forests are defined as those that have established following previous clearing or disturbance. Within the BRB, their extent has been mapped previously by Butler (2009) using time-series of 25 m spatial resolution Landsat FPC data. For the 12 REs in the BRB where brigalow is dominant or subdominant, and based on a threshold of 18 % applied to FPC data from 2004, Butler (2009) reported an area of 271,902 ha of regrowth in patches > 5 ha. The total area of regrowth in identified patches was calculated after multiplying by a modifier for regrowth age which down-weighted younger regrowth. Butler (2009) also reported the time since last clearing through reference to Statewide Land Cover and Trees Study (SLATS; Danaher *et al*., 2010) change-detection data for the periods 1991–1995, 1995–1997, 1997–1999 (based on Landsat sensor data) and direct time-series comparison of Landsat time-series data for each year from 2000 to 2005. The study highlighted that the more extensive areas of post-1991 regrowth had established on land that had been cleared between 1998 and 2001, a period when deforestation for agricultural expansion was particularly widespread. The majority of regrowth by percentage and area were found in REs 11.3.1, 11.4.3, 11.4.9, 11.4.9, 11.9.1 and 11.9.5. To date, no maps of forest degradation states have been produced for the BRB. An FPC threshold of 11 % is typically used by SLATS to distinguish forest and non-forest, although this does not capture the very early-stages of regrowth that typically support an FPC threshold of ≥ 9 % (Accad *et al*., 2010).

Whilst the extent of regrowth forests has been mapped, differentiation of stages of structural development has remained a significant challenge. This is particularly the case when using optical data as only the upper forest canopy is observed and the three dimensional distribution of plant material can only be inferred. Lucas *et al*. (2006) proposed that the earliest stage of regrowth of stands dominated by brigalow could be consistently mapped using AIRSAR and hence potentially ALOS PALSAR L-band data in combination with Landsat-derived FPC. These early regrowth forests are particularly widespread and prevalent on land cleared previously for agricultural purposes, and are characterised by a high density of stems (typically > 5000-8000 ha^{-1}) of low stature (< 5 m) that support a relatively open canopy (typically < 30 %) but with higher cover where clumps occur. Differentiation using AIRSAR data was achieved as the early-stage of regrowth supported an L-band HH backscattering coefficient similar to non-forest but an FPC equivalent to forest (with a 12 % FPC threshold used, equating to ~ 20 % canopy cover). The low response at L-band occurred because individual stems, although of high density, were of insufficient size (e.g., in terms of diameter and height) for strong double-bounce scattering to occur between the trunks and ground. Using the model of Durden *et al*. (1989) to simulate backscatter, Lucas *et al*. (2006) suggested that stems needed to be > ~4 cm in diameter (at breast height) and > ~2 m in height to generate a scattering response at L-band.

Differentiating more advanced stages of regrowth using these same combinations of data is more difficult as the increase in L-band HH and HV backscattering coefficient and Landsat FPC associated with the structural development of the forest ultimately results in a greater similarity with remnant forest. Similarly, defining degradation states relies on knowledge of the characteristics of the remnant forest. However, Accad *et al*. (2010)

established that forests known to be mature (primarily remnant) collectively supported a greater L-band HH and HV backscatter and Landsat FPC than earlier growth stages, with this attributed to the amount of plant material in the forest volume (as reflected in their height, basal area, canopy cover and biomass) being generally greater. Hence, by mapping both the remnant and early regrowth forests using the combination of ALOS PALSAR and Landsat FPC data, all remaining forests could be regarded as being of an intermediate growth stage or as degraded. On this basis, Clewley *et al*. (2012) classified early, intermediate and mature (including remnant) stages for a single RE (11.4.3) in the Tara Downs sub-region based on a statistical comparison (z-test) between the L-band HH and HV and Landsat FPC data extracted from image segments of unknown class with those associated with reference distributions extracted from areas where field data were available for each growth stage. Classification accuracies were > 70 % for all three stages and 90 % when only early-regrowth and mature (including remnant) stages were considered. The approach provided some flexibility in the mapping of the three stages given that ecological definitions can vary.

In this study, a combination of the approaches of Lucas *et al*. (2006) and Clewley *et al*. (2012) was considered, namely:

a) The integration of ALOS PALSAR L-band HH backscatter to provide a consistent approach to mapping the earliest stage of regrowth, with this explained by scattering theory and exploiting thresholds of FPC, as used by SLATS for producing annual maps of forest/non-forest across the State.

b) The use of L-band HH and HV and FPC data extracted from previously mapped areas of remnant vegetation, which could be compared to the same data from non-remnant areas, thereby allowing definition and mapping of mature and intermediate stages of growth and degradation.

c) Reference to existing Regional Ecosystem mapping (Queensland Herbarium, 2013b) and rainfall information (Busby, 1991), allowing within-region variations in the L-band HH and HV backscatter and Landsat FPC as a function of soils, land forms and climate to be accounted for.

The following sections therefore outline the combined method taken to mapping different stages of structural development across the BRB.

3. Materials and Methods

3.1 Available data

3.1.1 Remote sensing data

For the mapping of growth stage across the BRB, ALOS PALSAR L-band HH and HV Gamma0 (γ^0) data tiles, each covering 1^o x 1^o, were provided through the JAXA Kyoto and Carbon (K&C) Initiative at 25 m spatial resolution for 2009. Data were supplied orthorectified, slope-corrected, radiometrically calibrated, and radiometrically balanced for seasonal change between adjacent strips (Shimada and Ohtaki, 2010). These tiles were combined to generate a seamless mosaic for Queensland, which was masked to the

BRB extent. Landsat FPC data mosaics covering the BRB were generated as part of the SLATS program using standardised procedures outlined by Danahar *et al*. (2010) and Armston *et al*. (2009).

3.1.2 Vegetation data

For the BRB, a reference map of remnant forest extent for 2009 was provided by the Queensland Herbarium (Queensland Herbarium, 2012b). The original baseline map was generated through time-series comparison of aerial photography and optical satellite sensors, but refined in the years following by reallocating areas to a deforested category if clearance was observed within Landsat sensor data acquired subsequently under the SLATS program of annual Statewide reporting. In this approach, natural disturbance or degradation of forests (e.g., through fire or as a consequence of drought) was not considered.

3.2 Definition of reference distributions

In the preceding study of Clewley *et al*. (2012), which focused on the Tara Downs subregion, field data collected from 74 plots by Bowen *et al*. (2009) and Dwyer *et al*. (2010b) for RE 11.4.3 were assigned to mature forest when they supported > 70 % of the height and > 50 % of the cover compared to reference values from known areas of remnant forest in that RE (following the definition of Neldner *et al*., 2005). The definition was expanded to early-stage regrowth, which was defined as having less than 30 % of the height and cover, relative to reference values. All remaining plots were assumed to be at an intermediate stage of growth. Using data extracted from plot locations, distributions of L-band HH and HV and FPC for each growth stage were generated and used to support an object-based classification of these across the subregion. For this same technique to be extended to all 12 REs, field data providing height and cover were needed for each and for all growth stages contained, particularly given the known variability in forest structure between REs. Across Queensland, a program of establishing reference (BioCondition) sites is being implemented (Eyre *et al*., 2011), with data collected from each serving to capture the natural variation in the structure and species composition of mature or relatively undisturbed forests as a function of, for example, soils, topography and climate. However, such data are currently available for only a few REs and were insufficient to support the classification across the bioregion. Whilst CORVEG and some other reference data were available (see Table 1), the descriptions were too broad to allow a quantitative analysis. Hence, the method of defining distributions for all growth stages, based on plot data (Clewley *et al*., 2012) could not be applied. Therefore an alternative approach was applied, using only reference distributions of L-band HH and HV backscatter and Landsat FPC extracted from areas mapped as remnant by the Queensland Herbarium (2012b).

Using this map, all polygons representing remnant vegetation associated with each RE were buffered inwards by 200 m (to avoid edge effects) and a maximum of five points were located randomly within each (to avoid the inclusion of marginal areas), with none being closer than 500 m to another. This provided a total of 2858 points, with the number in each RE proportional to its area within the BRB (Table 3). Each point was then buffered by 100 m and L-band HH and HV and Landsat FPC values were extracted. For five of the REs the extent was < 10, 000 ha and hence only a very low number of points (< 50) could be established.

INSERT TABLE 3 HERE

Reference distributions of L-band HH and HV and Landsat FPC extracted for remnant forests for the seven REs with areas > 10,000 ha were therefore used as the basis for the subsequent classification. A One Way Analysis of Variance (ANOVA) was conducted within the R statistical package (R Core Development Team, 2012) to establish whether differences in the L-band HH and HV and Landsat FPC were significantly different between all REs. A Tukey Honesty Significant Difference (HSD) test (Steel & Torrie, 1980) was then used to determine which REs, if any, differed such that these could be grouped or considered separately in the subsequent mapping of regrowth stage. The tests were also used to establish whether there were differences in values within RE 11.9.5, which spanned an area from the inland to about 100 km from the coast and where rainfall ranges from < 500 mm to > 750 mm. For this analysis, two rainfall regimes either side of the 600 m isohyet were compared, with this selected as it approximated the median for the RE.

3.4 Generation of regrowth maps

Remnant forests had been mapped previously by the Queensland Herbarium and hence such areas were retained within the final growth stage map for the BRB. Within the remaining areas, a segmentation was undertaken by applying the algorithm of Shepherd *et al*. (2012), made available within RSGISLib (Bunting and Clewley, 2012), to the FPC/PALSAR mosaic to create image-objects with a minimum size of 1 ha (16 pixels). Following the definition of reference distributions for remnant vegetation for each RE, each object associated with forest (with an FPC ≥ 9 %) was assigned to a mature category where the distance of the average HH and HV backscatter and FPC for the object was one standard deviation away from the mean of the reference distribution. This differed from the use of *z*-scores proposed in Clewley *et al*. (2012), as reference distributions were only required for a single growth stage and the threshold was consistent, regardless of segment size. As described in Lucas *et al*. (2006), early regrowth exhibits a backscatter similar to non-forest as the stems and branches are of insufficient size to generate a strong response at L-band. To determine this value, random points were located within the pre-clearing extent of Brigalow and distributed across all REs. From these points, over 950 locations were classified as forest or non-forest, based on interpretation of very high resolution satellite imagery (e.g., Quickbird, WorldView) available through Google Maps. From each point, HH-backscatter was extracted for pixels within a 50 m radius. Based on these statistics, a value of -14 dB was determined to be the upper limit of non-forest regardless of the RE considered (Figure 3), with this explained by the similarities in the structure of early regrowth occurring within and between REs. This threshold was therefore used to separate early-stage from intermediate regrowth. Lucas *et al*., (2006) used this same threshold for differentiating early regrowth within RE 11.9.5 using AIRSAR data, which was also identified through backscatter modelling. All remaining forests not classified as remnant, mature or early regrowth were then assigned to an intermediate stage. This intermediate stage is associated with forests that have established on previously cleared land and are hence regenerating. However, these regenerating forests could also have degraded during the intervening period and hence this stage can be associated with a degradation category.

INSERT FIGURE 3 HERE

3.5 Assessment of classification accuracy

As with the determination of reference distributions, the assessment of accuracy was problematic because of the lack of field data for each of the REs. For this reason, a further 500 random points were selected from the area associated with each of the REs, with a buffer of 100 m then placed around each, which was clipped to the pre-clearing extent of the brigalow REs where necessary. These data were then interpreted visually with reference to very high resolution aerial photography and satellite imagery available through the Bing Server in ArcMap 10 (ESRI 2012). From the 500 points, 13 were considered invalid because of low quality imagery and were excluded leaving 487 points for assessing accuracy (Table 4).

INSERT TABLE 4 HERE

Examples of the appearance of the three growth stages in true colour aerial photography as well as remnant forest are provided in Figure 4. Early-stage regrowth was associated with vegetated landscapes with sparse to dense canopies of low stature (indicated by the comparative lack of shadows). Similarly, mature forests were associated with trees that were visually taller (again, determined through reference to shadow and, to a lesser extent, crown size), with these often occurring in relatively dense stands of high cover. The assignment to a mature stage was undertaken with reference to stands that were known to be remnant. Whilst structural variation was observed between REs for remnant forests, most were typically associated with taller trees although openness varied depending on whether these were woodlands, low open forest or forest (Specht, 1970). Photo plots not assigned to an early regrowth or mature category were associated with the intermediate stage of growth (or a degraded state), with this being the most variable in terms of structure.

The accuracy of the remnant class was not considered as this used existing mapping (Queensland Herbarium 2012b). In each case, and to better explain errors noted in the confusion matrix, the tree cover was estimated according to categories of < 5 %, 10 %, 25 % and 50 % and > 50 %, 75 % and 90 %. The distribution of trees across the area was also described as being either evenly distributed (i.e., relatively uniform within the 100 m radius circle) or clumped.

INSERT FIGURE 4 HERE

4. Results

4.1 Differences between REs

One Way ANOVA indicated significant differences ($p < 0.001$) in the distributions of L-band HH ($F = 73.55$) and HV ($F = 87.39$) and Landsat FPC ($F = 93.15$) for remnant forests between REs, suggesting that a single distribution could not be used for discriminating and classifying relative stages of growth across the BRB. For the seven REs where regenerating forests occupied more than 10,000 ha (i.e., 11.3.1, 11.4.3, 11.4.7, 11.4.8, 11.4.9, 11.9.1 and 11.9.5), separate distributions of L-band HH and HV and Landsat FPC were generated as the Tukey HSD test indicated significant differences ($p < 0.001$) in at least one variable between these as well as the smaller REs. The exception was RE 11.9.1 (n=279) and RE 11.3.1 (n = 371) but a separate distribution was nevertheless used for consistency. RE 11.9.5 occurred from the coastal margins to the interior, and hence separate distributions were generated for remnant forests occurring either side of the 600 mm isohyet. Significant differences in the two ALOS PALSAR polarisations were observed between the remnant populations in these zones. Separate distributions were not used when the area of remnant in 2009 was < 10,000 ha and the sample size was < 50, because of their limited extent. For these, and based on the Tukey HSD outcomes, the distributions of L-band HH and HV and Landsat FPC for remnant forests in REs 11.11.4 and 11.12.21, which were both confined to a narrow zone along the coastal margin and supported similar values in all data variables, were associated with forests occurring in the higher rainfall zone of 11.9.5. Remnant forests in RE 11.9.6, the total area of which was 18 ha, were also associated with the more expansive forests of this zone. REs 11.4.10 and 11.5.16 were linked to 11.4.3, noting that 11.5.16 is in the north and closer to but not on the coast. The distributions for all REs (with the exception of 11.9.6) are presented in Figure 5.

INSERT FIGURE 5 HERE

4.2 Maps of regrowth stage in areas dominated previously by brigalow.

The extent of early, intermediate (including degraded) and mature growth stages was estimated within the area of the 12 REs in the BRB mapped as non-remnant in 2009 by the Queensland Herbarium (2012b). These areas were combined with the remnant vegetation mask to produce a map of all four growth stages in the 12 REs (Figure 6). The Queensland Herbarium maps of remnant forest, where one of the 12 brigalow REs considered was the dominant component, were substituted into the map as these were produced using a wide range of remote sensing and ground data sources to support reporting obligations at the national and international level, and represented the best available mapping. Several areas outside of the remnant mask were assigned to the mature growth stage and were highlighted as they potentially represented forests that had recovered sufficiently from previously disturbance and hence could have attained a structure similar to remnant vegetation. Within some remnant areas, lower values of L-band backscatter and/or FPC were observed suggesting that these might have experienced degradation or disturbance through natural events and processes (e.g., fire, drought). The area estimates for each growth stage, by RE, are provided in Table 5, with these taking into consideration the proportion of separate brigalow REs within each polygon, defined using the pre-clearing extent.

INSERT FIGURE 6 HERE

INSERT TABLE 5 HERE

Within the 12 REs, a total forest area of 1,183,185 ha was mapped in 2009, with the most extensive being (in descending order) within REs 11.9.5, 11.4.9, 11.4.3, 11.4.8 and 11.3.1 (Table 5). Within this area, 460,499 ha (38.9 %) were mapped as remnant and the remaining 61.1 % as early (368,473 ha; 31.1 %), intermediate (230,551 ha; 19.5 %) and mature (123,662 ha; 10.5 %) growth stage. The extent of early regrowth was > 50,000 ha within REs 11.4.8, 11.4.9 and 11.9.5 and represented more than a third of the area in REs 11.4.8 and 11.4.9 and 11.9.1. Forests at the intermediate stage of growth (including degraded) typically occupied between 15 and 25 % of the REs, although the area was least for REs 11.4.8 and 11.11.14. Forests at the mature stage of growth occupied between 10 and 20 % of most REs and were most extensive within RE 11.12.21 and least for REs 11.3.1, 11.4.9 and 11.9.1. Remnant forests typically represented between 33 % and 58 % of forest growth stages, reflecting the lack of secondary forests in many REs.

The area of each growth stage as a proportion of the total within each RE is indicated in Table 6. RE 11.9.5, being the most extensive ecosystem supported the largest area of early, intermediate (including degraded forest) and mature growth stages as well as remnant forest. The greatest proportion (between 10.2 % and 19.2 %) of forests in the intermediate stage was located within REs 11.3.1, 11.4.3, 11.4.9 and 11.9.1, mature stages were more extensive within REs 11.4.3 and 11.4.8 and remnant forests were largely within REs 11.4.9, 11.4.3 and 11.4.8.

INSERT TABLE 6 HERE

4.3 Accuracy assessment

The overall accuracy in the classification of non-forest and the three stages (early, intermediate and mature) was 77.8 % (Table 7), with a kappa value of 69.0 %. Users' accuracies exceeded 80.0 % for non-forest and early regrowth but were lower for intermediate and mature regrowth (61.1 % and 55.3 % respectively). Producer's accuracies were 87.8 % for non-forest, 68.8 % for early regrowth and 71.3 % and 91.3 % for the intermediate and mature forests respectively. The confusion was greatest between regrowth classes and particularly between the intermediate and mature stages. Confusion was also greatest between categories where assignments to a class within the very high resolution imagery were compromised by the comparatively low canopy cover and particularly where a clumped spatial distribution was observed. However, when the mature and intermediate stages were combined, the overall accuracy increased to 85.8 % (kappa value of 73.6 %) whilst the Users' and Producers' accuracies increased to 71.2 % and 89.1 % respectively (Table 8).

INSERT TABLE 7 HERE

INSERT TABLE 8 HERE

5. Discussion

5.1 Defining and mapping growth stages

For the BRB, several forest growth stages were classified using single-date ALOS PALSAR data acquired under relatively dry conditions (as recommended by Lucas *et al*., 2010) and FPC generated from Landsat sensor data acquired over the course of a single year. By combining these data, the complexity of handling long inter-annual time-series of data (e.g., in terms of pre-processing, classification, post-processing and error propagation) to estimate forest age or track changes in retrieved biophysical attributes (e.g., biomass, canopy cover) over time was largely overcome. Furthermore, each stage could be associated with a structural description and differentiated on the basis of thresholds that represent relatively distinct structural transitions. The approach nevertheless has limitations including the requirement for a high level of accuracy in the co-registration of the SAR and Landsat sensor data.

The extent of forest cover and differences between growth stages (including degraded forest) were determined using thresholds of L-band HH and HV and FPC that were interpretable on the basis of ecological knowledge but also differences in the microwave scattering mechanisms occurring (Lucas et al., 2006). To separate more scattered areas of regrowth forests in the very early-stages of development, a relatively low FPC threshold of 9 % was used. Reference to very high resolution imagery available in ArcMap 10 (ESRI, 2012) suggested that this lower FPC threshold captured most of the woody vegetation at the earliest stage of regeneration in the forest mask. However, this required that the cover of vegetation within unit areas was sufficient, which most often occurred when tree crowns were distributed rather than clumped. Different FPC thresholds have been used for mapping woody vegetation and specifically regrowth. Lucas *et al*. (2006) used a threshold of 12 %, with this equating to approximately 20 % canopy cover in Australia (a common definition of forest cover), as this provided a more robust classification of the early-stage of regrowth. Butler (2009) used a threshold of 18 %, recognising that this provided a conservative estimate as only the more advanced stages of regeneration were captured. As these thresholds of FPC are raised, a corresponding decrease in the area of regrowth (particularly in the early-stage) and hence forest will occur. For example, when the FPC threshold used to define the forest (including regrowth) and non-forest boundary was raised from 9 % to 12 %, the forest area (both dominant and subdominant) within the 12 REs reduced by 8.0 %, with approximately 10 % of photo plots determined as containing early regrowth then assigned to non-forest. When an 18 % threshold was used, the forest area reduced to 32 %, and 25 % of regrowth photo plots were assigned to non-forest. Additionally, the reported accuracy in the maps of regrowth forests will vary depending upon the reliability of the interpretation of the photo plots images and also the spatial distribution of stands within the sampled area, with more distributed stands being better represented than those that are clumped. In addition, the spatial resolution of the observing sensor in relation to the spatial configuration of regrowth needs to be considered as variability in the size and shape of stands of regrowth stands can impact on the success of detection. This is an important consideration when applying the approach developed in this study to other currently operating and planned higher resolution optical (e.g., SPOT sensor) and SAR (e.g., PALSAR-2) data. Future work should therefore focus on the optimisation of approaches (e.g., thresholds) for defining forest and non-forest and separating different growth stages across large areas and over time using time-series of single Landsat FPC and also L-band SAR data. For this purpose, this study has established the need for more extensive and targeted field and ideally LIDAR data acquisitions (including for remnant forests within each RE) to allow each of the different stages (and particularly the remnant forests) to be better characterised in terms of relative differences in structure, particularly given the lack of sufficient field data from all stages and for all REs considered.

Within the early-stage of brigalow regrowth, the structural variability is generally lower and is dictated, in part, by the timing and methods used in the clearance of woody vegetation and in subsequent agricultural management or reclearance operations (Johnson 1964). Most studies of early regrowth have noted that these are generally of a higher density compared to more advanced stages with other biophysical attributes being less discriminatory. In particular, the stem densities observed in young regrowth far exceed those observed within remnant forests as well as more advanced stages of regrowth. For example, Johnson and McDonald (2005) reported 28,000 stems ha^{-1} within nine months of pulling and burning, and Dwyer *et al*. (2010b) found higher densities in patches cleared multiple times. In these high-density 'locked up' stands, the development of regrowth is often inhibited and they may remain structurally similar for decades until self-thinning releases resources for growth. As illustration, Johnson and McDonald (2005) also reported a maximum of 32,000 stems ha 15 years after burning with a decline to 22,000 ha and 13,000 ha after 27 and 37 years respectively. For 29-

year old stands, Dwyer *et al*. (2010a) reported mean densities of 17,000 stems ha. Even after 40 years, Dwyer *et al*. (2009) noted that regenerating forests still supported 14,000 stems ha. Ngugi *et al*. (2011) estimate that self-thinning would take 95 years to reduce high initial stem densities observed in brigalow regrowth to a level similar to that in remnant forests, which accords with the estimate of 100 years discussed by Dwyer *et al*. (2009) and Bowen *et al*. (2009). The extreme density of brigalow stems in many (but not all) young regrowth stands can also inhibit recruitment of other plant species, such as shrubs and smaller trees, that contribute to both floristic and structural diversity (Johnson and McDonald, 2005, Chandler *et al*. 2007, Bradley *et al*. 2010). These forests also differ in their height, with ‘locked-up’ stands rarely exceeding 7 m and progression into taller classes mainly occurring following thinning, either from natural causes or by intervention. For the reasons outlined above, the early-stage of regrowth are more homogeneous in structure within and between REs compared to later stages of growth and are also quite distinct structurally, with thinning (either through natural processes such as fire or management) being a stimulus for transition into the next stage (Fensham and Guymer, 2009).

Within a colour composite of Landsat FPC and ALOS PALSAR L-band HH and HV (in RGB), the earliest stage of regrowth is often distinct as it exhibits a red colouration because of the presence of a canopy (FPC in red) but lack of L-band HH and HV return (in green and blue respectively) from woody components which are too small for double-bounce or volume scattering to be significant; hence ground scattering away from the sensor occurs (Figure 7). The point at which the scattering mechanism changes (i.e., from ground scattering to both volume scattering from the canopy and double-bounce scattering from trunk-ground interaction) effectively defines when trees are of a sufficient size and density to generate a response at L-band with this defining the transition between a 'locked up' stand and a more advanced (i.e., intermediate) stage of growth. Lucas et al. (2006) established, through modelling, that this threshold approximates -14 dB at L-band HH, which is supported in this study. The stage of transition does not, however, equate to the age as many stands remain in a 'locked-up' state for several decades. Hence, the approach to mapping again presents a major advantage over time-series analyses in that the structural development rather than the age of stands is captured. Nevertheless, the integration of growth stage maps generated using SAR and Landsat FPC data with age class but also land use maps generated from time-series data (including of FPC) provides a unique insight into the dynamics of brigalow regrowth as a function of land management history. This earliest stage can also be associated with a structural description (i.e., often exceeding 10,000 stems ha^{-1} with a height of < 2-3 m and a FPC > 9 %) that can be used to explain its manifestation within composites of Landsat FPC and L-band HH and HV data. In strong contrast to early regrowth, remnant forests collectively exhibit a high FPC and L-band HH and HV backscatter and hence their white appearance in the same colour composite.

INSERT FIGURE 7 HERE

The intermediate growth stage, which also can be a degradation category, is the most complex to define as structural variability is high because of the influences of both the physical environment as well as human intervention and natural events (e.g., fires) and processes (e.g., dieback following water logging or drought). For this reason, these forests are defined as those that are not classified as early regrowth or mature forests. As with remnant forests, the characteristics of mature forest will vary between REs as a function of, for example, climate and landform (i.e., soils/geology and topography). Therefore, the use of a separate threshold for each RE is justified, with this defined with respect to the distribution of L-band HH and HV for known areas of remnant forests within each RE. Forests in the mature stage of growth may support a biomass and cover similar to remnant forests and hence these cannot be distinguished using L-band HH and HV (because of the known issues of saturation of the backscatter above certain biomass levels; Lucas *et al*., 2010) or Landsat FPC data. However, as the extent of remnant is known, mature forests can be separated within the BRB. Knowledge of their extent is particularly important given that these are most likely to be structurally similar to remnant forests and hence long-term conservation can facilitate their potential transition to a remnant forest in future years. The forests mapped outside of the remnant mask may also support high conservation or carbon values that have not yet been identified.

The use of a one standard deviation threshold applied to HH and HV and FPC data was considered to represent those forests that were not remnant but which most closely resembled the structure of the remnant stage. This threshold can be varied but should reference structural information obtained through field or LIDAR measurements of remnant and mature forests. The threshold used resulted in some areas known to be remnant being assigned to a mature or intermediate stage prior to merging with the

Queensland Herbarium remnant mapping. Such areas were highlighted for further investigation as they represent remnant vegetation that is most likely to be structurally different (e.g., of lower density) from that which is typical and may have experienced disturbance. The use of inter-annual time-series of Landsat and even SAR data to establish the extent and magnitude of structural changes within remnant forests is therefore advocated.

In summary, the mapping has defined early-stage regrowth on the basis of a transition from single-bounce to a double-bounce scattering at L-band following attainment of a certain stem size and density. The mature stage of growth is assumed, in the field, when forests support at least 70 % of the height and 50 % of the cover of remnant forests of the same type. Using remote sensing data, forests are assumed to have transitioned to a mature stage when they collectively support an L-band HH and HV and FPC within one standard deviation of the distributions for remnant vegetation identified for each RE. Within each RE, the structure of forests within the mature stage can then be inferred from knowledge of remnant forests. Intermediate forests, including those that are degraded, support a structure that is between that of the early regrowth and mature forests. In all cases, the age at which these transitions occur is highly variable. Therefore, assigning structural descriptions to each growth stage class is difficult given this high degree of variability as a function of factors including management (e.g., thinning), fire and environment (e.g., rainfall, soils). Whilst a greater number of growth/degradation stages could be been defined or a more quantitative description provided, this requires a greater amount of ground truth data to characterise the different stages across their range and/or reference to validated structural measures derived from, for example, the ALOS PALSAR data themselves (e.g., biomass) or ICESAT (e.g., height profiles). This is the subject of ongoing research.

5.3 Relationships to agricultural land use

The observed distribution of the different growth stages within the BRB reflects the past history of vegetation clearance and subsequent use of the land, as outlined by Seabrook *et al*. *(*2006) and Accad *et al*. (2008). Between 1950 and 1997, clearance operations focused primarily on REs 11.9.5, 11.4.3, 11.4.8, 11.4.9 and 11.3.1 and these forests continued to be cleared from 1997 onwards. These same REs also supported the greatest amount of early-stage regrowth (between 22.6 and 42.1 % of the RE). From 1997 onwards, forests within REs 11.4.7 and 11.9.1 were also cleared, with the relatively high proportions of early regrowth (24.4 % and 21.3 %) reflecting resprouting in the periods following.

Whilst the early-stage of regrowth is extensive, this should not be construed as widespread land abandonment. Often, these forests are artefacts of recent clearing and occur (although not exclusively) in REs that had previously seen the highest level of clearing (e.g., 11.3.1, 11.4.9, 11.4.3). Common practice is to re-clear these patches to eventually establish pasture free of brigalow regrowth (Seabrook *et al.*, 2007). In many of the more extensive REs, the extent of intermediate and mature forests was less than early-stage regrowth, which reflected the high rates of clearing of these forests and their subsequent initial regenerative response. These patches of early-stage forest regrowth represent a substantial opportunity for this threatened ecological community and the landscapes of the BRB.

5.4 Implications for carbon budgets and biodiversity

The clearance of forests with the BRB has lead to declines of over 90 % in the extent of most REs with brigalow as dominant, with 11.9.6 being reduced to 1.3 % of its former extent (Table 9). The exception is RE 11.5.16, where 22.1 % of forests are regarded as remnant. Overall, only 6.7 % of the total area of the 12 REs is remnant. However, when forests of all growth stages are considered, a greater proportion (17.2 %) of the former extent remains suggesting significant potential for ecosystem restoration. If the area of endangered REs could be increased to > 10 % of their original extent, this would technically mean they could be downgraded to “Of Concern” status (the remnant extent for endangered status under Queensland’s vegetation laws is less than 10% of the original, pre-clearing extent) (Sattler and Williams 1999). However, by restoring 15 %

to the equivalent of a remnant state, a 5 % buffer in area is provided that protects against unavoidable clearing or accidental loss (Butler, 2009). Particular attention needs to be focused on RE 11.9.6 as even with regenerating forests, only 4 % of the original ecosystem is remaining and very few areas are in regeneration (2.7 %). With this exception, between 2.5 % and 9.4 % of the original area of all REs is occupied by the earliest stage of regrowth. Efforts to avoid reclearance of this regenerating forest and to manage these more effectively to restore both carbon and biodiversity are advocated.

INSERT TABLE 9 HERE

If restoration of Brigalow habitat through regrowth can occur before the expected time lag between habitat reduction and species extinction, the benefits would be significant to biodiversity conservation and to landscape function in the BRB (McAlpine *et al.,* 2002, Wearne *et al.,* 2012). Emerging markets for the ecosystem service of carbon sequestration could help to fund this substantial change and provide additional income streams for rural economies (Fensham and Guymer 2009). For many land holders, economic incentives may change negative attitudes towards regrowth and this step is critical if the extents of brigalow ecosystems are to be increased to > 10% of their former extent (Seabrook *et al*. 2008). Spatial data on regrowth extent and structure development, such as those produced by this study might provide a powerful planning tool for the optimal delivery of such incentives.

As well as identifying areas for future restoration, the maps of forest growth stage for the 12 REs provide a basis for refined estimates of biomass and carbon in vegetation for the BRB, either through extrapolation of field-based estimates or using relationships established with remote sensing data, including ALOS PALSAR (Lucas *et al.,* 2010) and/or the Ice, Cloud, and land Elevation Satellite (ICESat). The mapping can further be used to estimate the carbon potentially accumulated by forests at different stages of growth and as a function of prior land use history (e.g., by integrating SLATS land cover change datasets) and environment (e.g., by integrating forest productivity models). Such knowledge assists also planning for restoration of the endangered brigalow ecosystems within the BRB.

The information on the structural development of regrowth has implications for quantifying biodiversity values associated with regenerating vegetation. For example, Bowen *et al*. (2007) highlighted studies that noted that the richness and abundance of flora increased as forests aged but also indicated the preference of some species within the BRB (e.g., ground dwelling fairy-wrens (*Malurus sp*) and the endangered bridled nail tail wallaby (*Onychagalea fraemata*)) for regrowth rather than mature stands. Bowen *et al*. (2009) also noted that the age of regrowth in part reflected the increase in structural diversity and was an important indicator of woodland bird species richness with the BRB. Kavanagh *et al*. (2007) and Munro *et*. *al*. (2011) found that after 20 years of establishing "ecological" plantings, the bird species richness was similar to remnant patches. As indicated earlier, the classifications of growth stage undertaken in this study are more reflective of the stages of structural development compared to those based on age and hence can be used to better support efforts at assessing, conserving and restoring the rich diversity of flora and fauna typically associated with brigalow-dominated ecosystems.

6. Conclusions

Using a combination of ALOS PALSAR HH and HV data and Landsat-derived FPC (derived from time-series), a structural (growth stage) classification of forested REs dominated by brigalow has been generated. Estimates of extent are provided based on the use of specified thresholds (FPC of 9 % for forest, L-band HH of -14 dB for early regrowth and, for mature forests within each RE, 1 standard deviation away from the mean FPC and both L-band HH and HV of remnant forests; remaining objects are assigned to an intermediate stage) and associated errors (77.8 % overall for non-forest, early, intermediate and mature growth stages and 85.8 % when the latter two were combined). Whilst previous studies (Lucas *et al*., 2006; Clewley *et al*., 2012) have highlighted the benefits of integrating these data, this study is the first to demonstrate mapping at a regional level. The differentiation of growth/degradation stage has also benefited from the existing mapping of REs as well as pre-clearing and remnant vegetation.

Three growth/degradation stages (early, intermediate and mature) have been consistently defined through reference to existing mapping of remnant forest and understanding of microwave interactions with components of the forest structure (e.g., for discriminating early and intermediate regrowth/degraded forest). Whilst the broad structural characteristics of each stage can be described from existing data, additional quantitative information is needed (e.g., through biocondition surveys) as these vary between RE and as a function of environmental conditions. The collection of such data can, however, be targeted for different REs and growth/degradation stages now that the maps have been generated.

The method adopted overcomes the need for extensive time-series of, for example, Landsat sensor data to determine age. However, such temporal data and derived products should be used in combination to better understand the dynamics of regrowth and also the impacts of land management practices. Further information can be discerned from the SAR data themselves, including clearing mechanisms, such as pulling, burning and blade ploughing (Lucas *et al*., 2008). ALOS PALSAR and ICESAT GLAS data might also be integrated to better quantify the biomass and structural attributes (e.g., height profiles) or the different forest growth/degradation stages.

Whilst the 12 brigalow-dominated REs have collectively been reduced to 6.7 % of their former range, rendering them endangered according to Queensland's vegetation laws., the extent of these remnant forests has remained relatively stable since the turn of the century. Furthermore, forests have regenerated at various times on an additional 10.5 % of land cleared previously for agriculture (based on an FPC threshold of 9 %). Hence, through conservation and restoration management of these forests to the equivalent of a remnant state, the brigalow ecosystems can potentially be taken into a safer "Of Concern" status.. However, 31.1 % of forests are in the early-stage of regrowth and a common practice is to reclear these, which prevents these forests from maturing. Hence, substantial changes to land management policies and practices are needed to ensure this transition in status. In this regard, the maps generated can be linked with estimates of biomass (carbon), carbon potential and biodiversity, with these potentially linked to monetary values that might encourage their long-term conservation and restoration.

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Tables
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Table 1. Characteristics of the 12 REs with brigalow as dominant within the Brigalow Belt Bioregion (Regional Ecosystems Description Database; Queensland Herbarium, 2012c). The first number denotes the bioregion (11 for the BRB), the second the landzone and third the vegetation community.

RE	Height (m)[cd]	Cover (%)[c]	Dominant/co-dominant species	Landforms and soils
11.3.1	11-15	10-70	*Acacia. harpophylla* and/or *Casuarina cristata; Eucalyptus* emergents. Shrub layer (2-8 m) with *Eremophila mitchelli* and *Geijera parviflora*	Alluvial plains
11.4.3[a]	10-18	30-70	*A. harpophylla* and/or *C. cristata*	Cainozoic clay plains
11.4.7	6-18	30-70	*Eucalyptus populnea* with *A. harpophylla* and/or *C. cristata;* shrub layer with *E. mitchelli* and *G. parviflora*.	
11.4.8	10-18	10-70	*E. cambageana* with *A. harpophylla* or *A. argyrodendron;* shrub layer of ~2 m.	
11.4.9 [a]	11-17	30-70	*A. harpophylla* with *C. cristata* and occasionally *Lysiphyllumn cunninghamii; Terminalia oblongata* and *Eremophila mitchelli;* mid story of 2-8 m and shrub layer of 1-2 m.	
11.4.10	16-26	10-30	*E. populnea* or *E. woollsiana*; understorey of *A. harpophylla* or *C. cristata*	Margins of Cainozoic clay plains
11.5.16	9-15	30-70	*A. harpophylla* and/or *C. cristata*	Depressions on Cainozoic sand plains/remnant surfaces
11.9.1	12-18	10-70	*A. harpophylla-Eucalyptus cambageana* or *E. thozetiana* with shrub layer containing *E. mitchelli, Carissa ovate* and *Geijera parviflora and T. oblongata*	Cainozoic fine-grained sedimentary rocks
11.9.5	10-20	30-70	*A. harpophylla* and/or *C. cristata* and vine understorey; shrub layer with *E. mitchelli* and *G. parviflora*.	
11.9.6	15	50-84[b]	*A. melvillei* ± *A. harpophylla* with *E. populnea*.	
11.11.14	5-10	30-70	*A. harpophylla* with low *E. mitchelli and G. pariflorva*	Deformed and metamorphosed sediments and interbedded volcanics
11.12.21	9-14	30-70	*A. harpophylla;* with vine thicket or shrub layer with *E. mitchelli and G. pariflorva*	Igneous rocks; colluvial lower slopes

[a]Shrubby open forest but open forest otherwise; [b]Fensham and Fairfax (1997); [c]Queensland Herbarium (2012c); [d]McDonald and Dilleward, (1994)

Table 2. Changes in the area of remnant forest with brigalow as a dominant or subdominant component from pre-clearing to the late 1990s/2000s (Accad *et al*., 2012). The forest area remaining as a percentage of the pre-clearing area for all REs is given in brackets.

RE	**Pre-clearing**	**1997**	**1999**	**2000**	**2001**	**2005**	**2006**	**2007**	**2009**
11.3.1	786425	96009 (12.2)	88100 (11.2)	84174 (10.7)	82989 (10.6)	81372 (10.3)	81154 (10.3)	81108 (10.3)	80877 (10.4)
11.4.3	1551852	96362 (6.2)	82994 (5.3)	78009 (5.0)	77477 (5.0)	76095 (4.9)	75996 (4.9)	75779 (4.9)	75712 (4.9)
11.4.7	209741	36156 (17.2)	26604 (12.7)	22564 (10.8)	22097 (10.5)	20622 (9.8)	20590 (9,8)	20497 (9.8)	20384 (9.7)
11.4.8	721808	90623 (12.6)	81053 (11.2)	74728 (10.4)	73713 (10.2)	71483 (9.9)	71359 (9.9)	71272 (9.9)	71162 (9.9)
11.4.9	1006131	123917 (12.3)	112936 (11.2)	100877 (10.0)	98817 (9.8)	96383 (9.6)	96145 (9.6)	95981 (9.5)	95498 (9.5)
11.4.10	63123	6811 (10.8)	6675 (10.6)	6515 (10.3)	6506 (10.3)	6488 (10.3)	6482 (10.3)	6481 (10.3)	6461 (10.2)
11.5.16	13357	3491 (26.1)	3357 (25.1)	3336 (25.0)	3299 (24.7)	3180 (23.8)	3178 (23.8)	3178 (23.8)	3178 (23.8)
11.9.1	567885	63304 (11.1)	60359 (10.6)	57273 (10.1)	56606 (10.0)	55230 (9.7)	55165 (9.7)	55107 (9.7)	55028 (9.7)
11.9.5	2270741	197048 (8.7)	180239 (7.9)	172571 (7.6)	171020 (7.5)	167239 (7.4)	167005 (7.4)	166815 (7.3)	166571 (7.3)
11.9.6	15317	389 (2.5)	365 (2.4)	357 (2.3)	356 (2.3)	350 (2.3)	350 (2.3)	345 (2.3)	345 (2.3)
11.11.14	39801	5002 (12.6)	4952 (12.4)	4750 (11.9)	4704 (11.8)	4669 (11.7)	4669 (11.7)	4667(11.7)	4667 (11.7)
11.12.21	72569	7668 (10.6)	7284 (10.0)	6726 (9.3)	6703 (9.2)	6553 (9.0)	6529 (9.0)	6505 (9.0)	6481 (8.9)
TOTAL	**7318750**	**726780 (9.9)**	**654918 (8.9)**	**611880 (8.4)**	**604287 (8.3)**	**589664 (8.1)**	**588622 (8.0)**	**587735 (8.0)**	**586364 (8.0)**

Table 3: REs within the BRB dominated by brigalow and the number of sample points within each. Of the available sample points, 50 % were used for generating distributions of L-band HH and HV and Landsat FPC. Note, only areas with brigalow as a dominant component were considered whereas in Table 2, areas with brigalow as a subdominant component were also included.

RE	Area of remnant forest, 2009 (ha)	No. sample points
11.3.1	41763	317
11.4.3	69336	382
11.4.7	15758	86
11.4.8	56324	428
11.4.9	70873	485
11.4.10	5596	34
11.5.16	2832	28
11.9.1	40418	279
11.9.5	147539	751
11.9.6	204	11
11.11.14	3794	25
11.12.21	6063	42
Total	460499	2858

Table 4. The number of sample photo points interpreted into different growth stages and non-forest.

Growth Stage	Number
Early	144
Intermediate (including degraded)	101
Mature (excluding remnant)	46
Non-forest	196
Total	487

Table 5. The area and proportion of early, intermediate and mature growth stages and remnant vegetation within the remaining forests dominated by brigalow in 12 REs of the BRB (Note that forests with brigalow as a sub-dominant component are not included). Areas are scaled by the proportion of each RE within each polygon in the pre-clearing extent (up to five REs per polygon).

		Area (ha)									
RE	**Pre-clearing**	**Early-stage**		**Intermediate**		**Mature**		**Remnant**		**Total area ha (all stages)**	
11.3.1	668,770	36,938	(29.8)[a]	34,198	(27.6)[a]	10,944	(8.8)[a]	41,763	(33.7)[a]	123,843	(18.5[c], **10.5**[d])
11.4.3	1,542,078	39,052	(22.6)	44,354	(25.7)	20,123	(11.6)	69,336	(40.1)	172,865	(11.2, **14.6**)
11.4.7	191,102	9,165	(24.4)	6,752	(18.0)	5,932	(15.8)	15,758	(41.9)	37,607	(19.7, **3.2**)
11.4.8	646,596	60,739	(41.5)	12,593	(8.6)	16,854	(11.5)	56,324	(38.4)	146,510	(22.7, **12.4**)
11.4.9	932,691	82,860	(42.1)	37,991	(19.3)	4,904	(2.5)	70,873	(36.0)	196,628	(21.1, **16.6**)
11.4.10	57,582	1,780	(14.6)	2,644	(21.8)	2,135	(17.6)	5,596	(46.0)	12,155	(21.1, **1.0**)
11.5.16	12,797	903	(18.5)	584	(11.9)	572	(11.7)	2,832	(57.9)	4,891	(38.2, **0.4**)
11.9.1	524,056	37,465	(33.8)	23,631	(21.3)	9,469	(8.5)	40,418	(36.4)	110,983	(21.2, **9.4**)
11.9.5	2,176,007	95,148	(26.8)	64,016	(18.1)	47,761	(13.5)	147,539	(41.6)	354,464	(16.3, **30.0**)
11.9.6	15,317	113	(20.2)	84	(15.1)	157	(28.1)	204	(36.6)	558	(3.6, **< 0.1**)
11.11.14	34,609	1,142	(13.7)	1,927	(23.0)	1,502	(18.0)	3,794	(45.4)	8,365	(24.2, **0.7**)
11.12.21	71,350	3,169	(22.1)	1,777	(12.4)	3,310	(23.1)	6,063	(42.3)	14,319	(20.1, **1.2**)
Total (all REs)	6,872,955	368,473	(**31.1**)[b]	230,551	(**19.5**)[b]	123,662	(**10.5**)[b]	460,499	(**38.9**)[b]	1,183,185	(17.2)

Percentage area of [a]forest growth stages within each of the 12 REs (and in all rows in the same column below); [b]each growth stage within all 12 REs, including remnant forest; [c]all growth stages as a function of total RE area and [d]the total area of forest in 2009.

Table 6. The proportion of non-forest, early, intermediate and mature growth stages, and remnant vegetation within each RE in relation to the total area of each across the 12 REs. (Note that forests with brigalow as a sub-dominant component are not included)

RE	Non-forest	Early-stage	Intermediate	Mature	Remnant
11.3.1	9.6	10.0	14.8	8.8	9.1
11.4.3	24.1	10.6	19.2	16.3	15.1
11.4.7	2.7	2.5	2.9	4.8	3.4
11.4.8	8.8	16.5	5.5	13.6	12.2
11.4.9	12.9	22.5	16.5	4.0	15.4
11.4.10	0.8	0.5	1.1	1.7	1.2
11.5.16	0.1	0.2	0.3	0.5	0.6
11.9.1	7.3	10.2	10.2	7.7	8.8
11.9.5	32.0	25.8	27.8	38.6	32.0
11.9.6	0.3	0.0	0.0	0.1	0.0
11.11.14	0.5	0.3	0.8	1.2	0.8
11.12.21	1.0	0.9	0.8	2.7	1.3

Table 7. Classification accuracy for non-forest, early regrowth and both intermediate and mature stages based on photoplots.

Image classification	On screen interpretation of very high spatial resolution imagery				Total	Users' Accuracy
	Non-forest	Early	Intermediate	Mature		
Non-forest	172	5	3	1	181	95.0
Early	11	99	10	2	122	81.1
Intermediate	12	29	66	1	108	61.1
Mature	1	11	22	42	76	55.3
Total	196	144	101	46	487	
Producers' Accuracy	87.8	68.8	71.3	91.3		77.8

Kappa = 69.0 (95 % confidence interval = 64 % to 74 %)

Table 8. Classification accuracy for non-forest, early regrowth and intermediate/mature stages combined.

	On screen interpretation of very high spatial resolution imagery				
Image classification	**Non-forest**	**Early**	**Interm. Mature**	**Total**	**Users' Accuracy**
Non-forest	172	5	4	181	95.0
Early	11	99	12	122	81.1
Interm./mature	13	40	131	184	71.2
Total	196	144	147	487	
Producers' Accuracy	87.8	68.8	89.1		85.8

Kappa = 73.6 % (95 % confidence interval = 69 % – 79 %)

Table 9. Summary statistics for those areas classified as brigalow, relative to the pre-clearing extent of REs with brigalow as a dominant component.

RE	Remnant	All growth stages[1]	Early to mature	Early
11.3.1	6.2	18.5	12.3	5.5
11.4.3	4.5	11.2	6.7	2.5
11.4.7	8.2	19.7	11.5	4.8
11.4.8	8.7	22.7	14	9.4
11.4.9	7.6	21.1	13.5	8.9
11.4.10	9.7	21.1	11.4	3.1
11.5.16	22.1	38.2	16.1	7.1
11.9.1	7.7	21.2	13.5	7.1
11.9.5	6.8	16.3	9.5	4.4
11.9.6	1.3	3.6	1.3	0.7
11.11.14	11	24.2	13.2	3.3
11.12.21	8.5	20.1	11.6	4.4
Total	**6.7**	**17.2**	**10.5**	**5.4**

[1]Including remnant

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Figure 1. a) The location of the Brigalow Belt Bioregion (BRB) in Queensland and the pre-clearing extent of Regional Ecosystems (REs; Queensland Herbarium, 2012a) with brigalow as a dominant component. b) Rainfall zones within the BRB extracted from 250 m spatial resolution BIOCLIM models for Queensland (Busby, 1991).

Figure 2. Variations in a) basal area, b) biomass, c) median canopy height, d) stem density and e) canopy cover as a function of the age of several forest REs dominated by brigalow and distributed across the BRB (Data from Bowen *et al*. (2009) and Dwyer *et al*. (2010b)).

Figure 3. Distribution of L-band HH backscatter values extracted from over 950 areas of forest and non-forest located across the 12 REs where brigalow dominates. The mean (thick line) and standard deviation for the box (± 1) and whiskers (± 2) are indicated.

Figure 4. Aerial photographs showing areas of a) early, b) intermediate (including degraded), c) mature growth stages and d) remnant forest dominated by brigalow. Areas of early regrowth are typically lower in stature (as evidenced, in part, by the lack of shadowing). Variability between REs is a function of these being open forest, low open forest or woodland and differences in associated species. Sample areas (100 m radius) for the early, intermediate and mature growth stages are clipped to the pre-clearing extent of brigalow-dominated REs.

Figure 5. The distribution of HH and HV backscatter (γ^0) and FPC for points within remnant brigalow mapping split by dominant RE. Boxplots use the mean (thick line) and standard deviation for the box (± 1) and whiskers (± 2), in contrast to the standard Tukey boxplot. The dashed red line represents the mean of all REs in for each variable. Only a single point was available for 11.9.6, and therefore statistics could not be calculated.

Figure 6. a) The extent of cleared areas and early, intermediate (including degraded forest) and mature growth stages of REs with brigalow as a dominant component mapped using a combination of ALOS PALSAR L-band HH and HV data and Landsat FPC (2009). Vegetation mapped previously as remnant in 2009 using time series aerial photography and satellite imagery (Queensland Herbarium, 2012b) is also shown. Detailed views of the classification are shown for the b) Injune Landscape Collaborative project (Tickle *et al*., 2006) and b) Tara Downs subregion (Bowen *et al*., 2009).

Figure 7. The manifestation of early regrowth forests (red) in a composite of Landsat FPC and ALOS PALSAR L-band HH and HV data in RGB for the Injune Landscape Collaborative Project (ILCP). Remnant forests appear brighter because of collectively high values in all channels. PALSAR data © JAXA/METI.

Figure 1a

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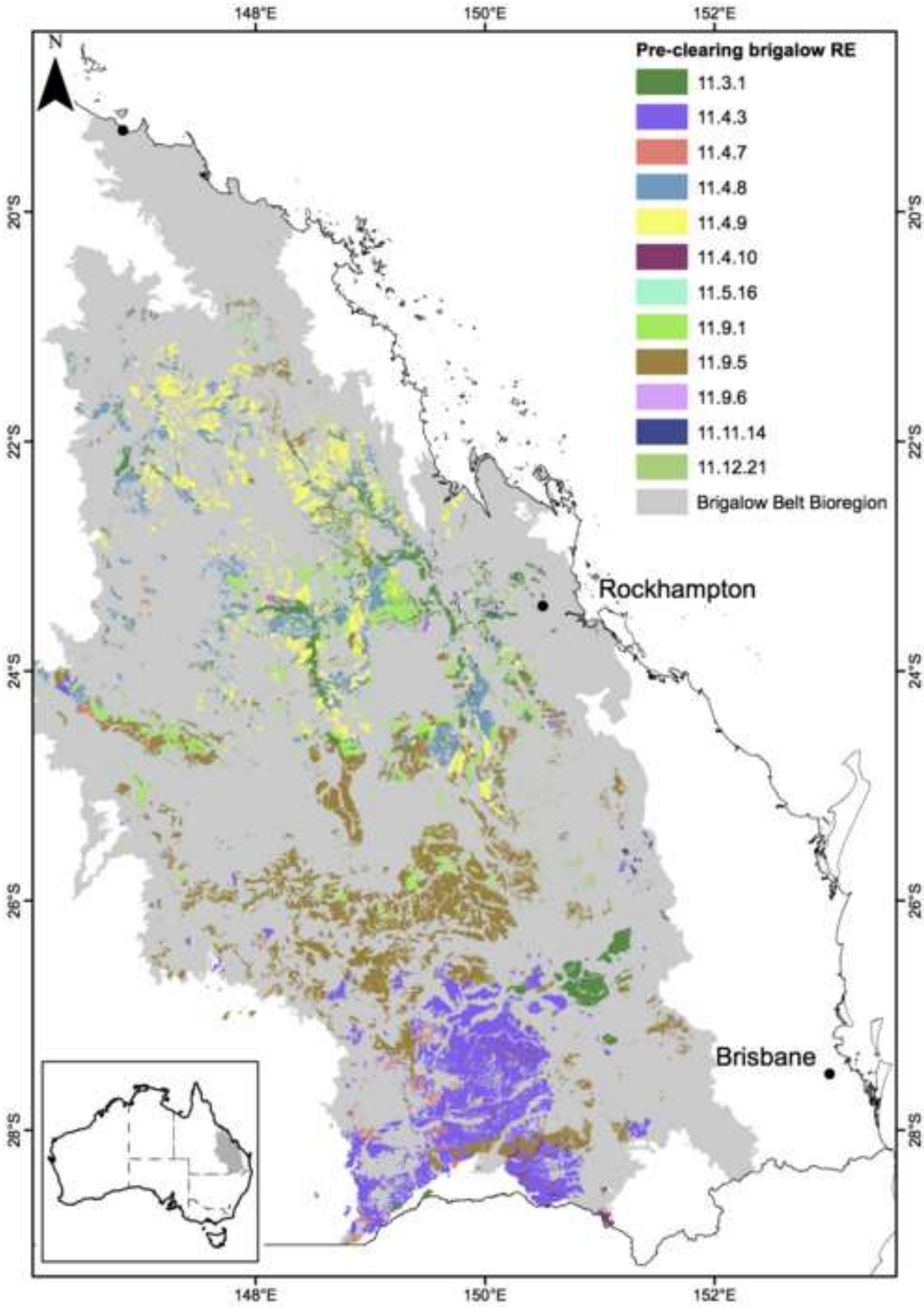

Figure 1b
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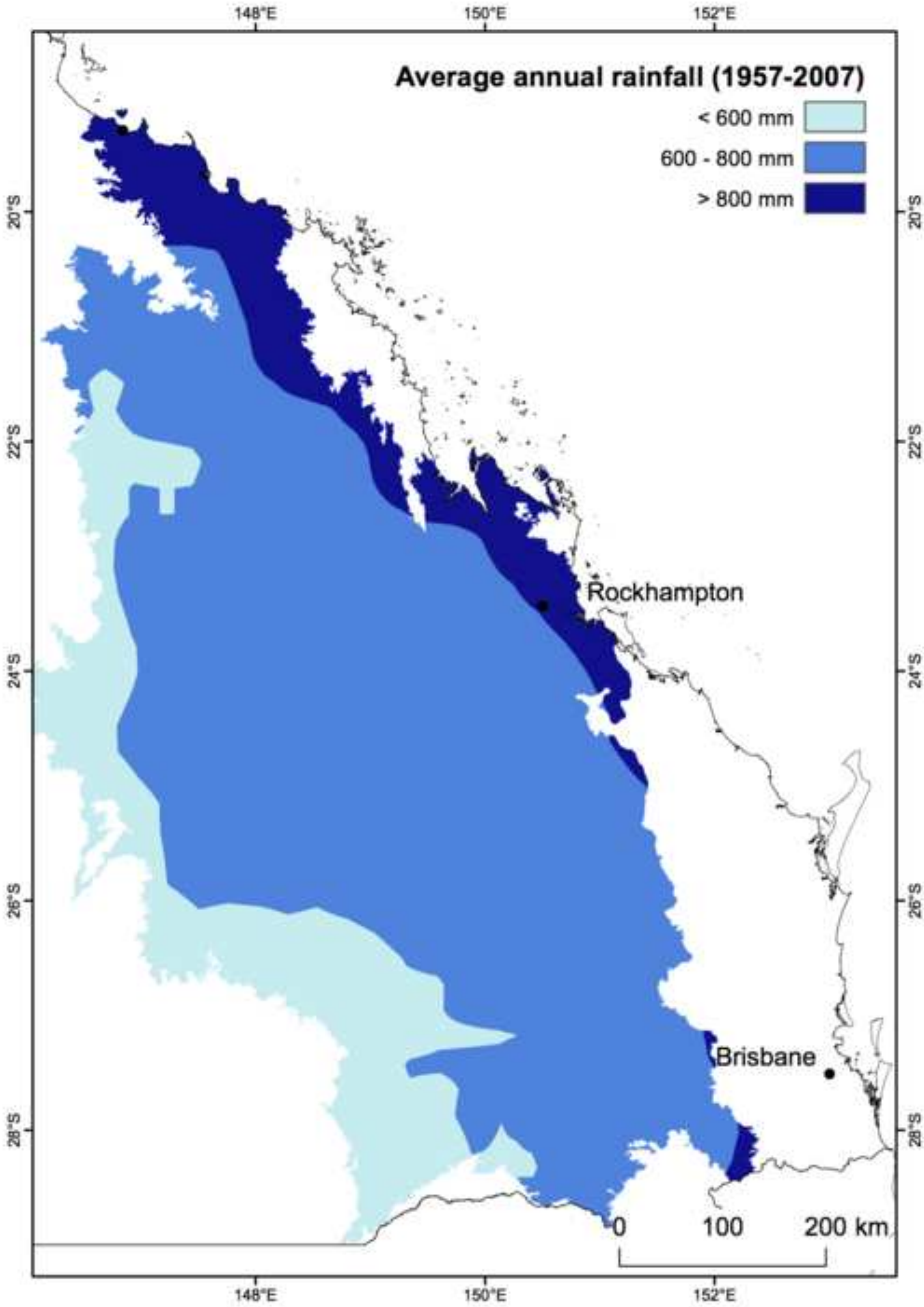

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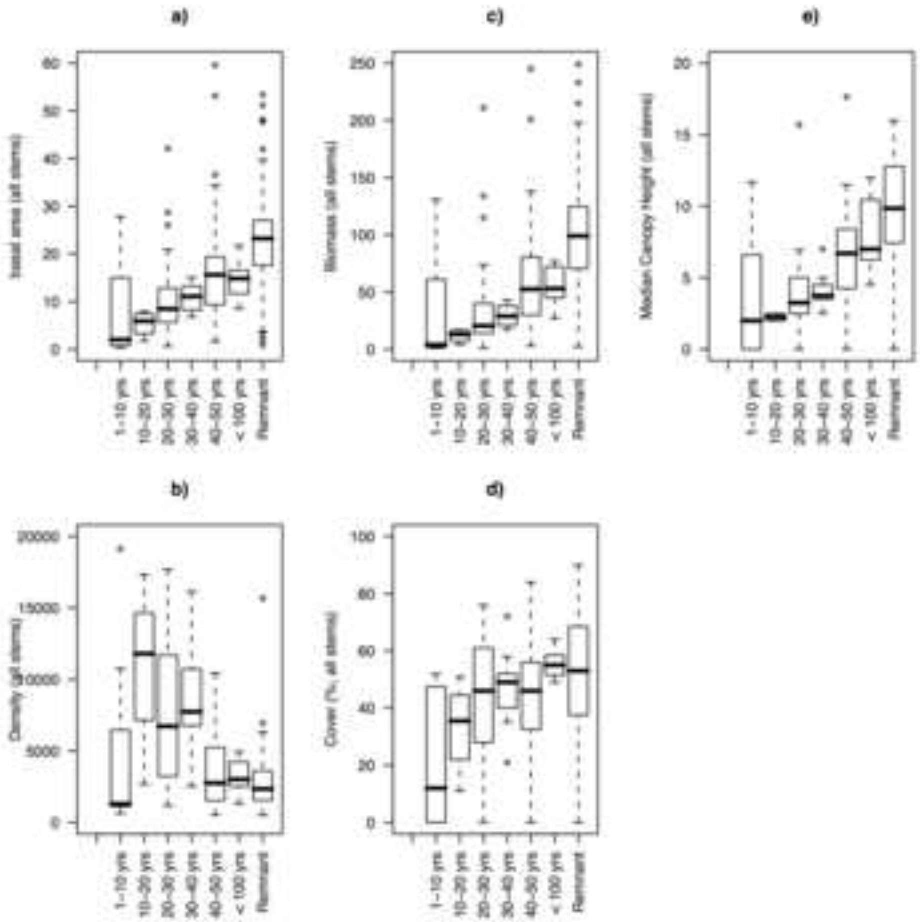

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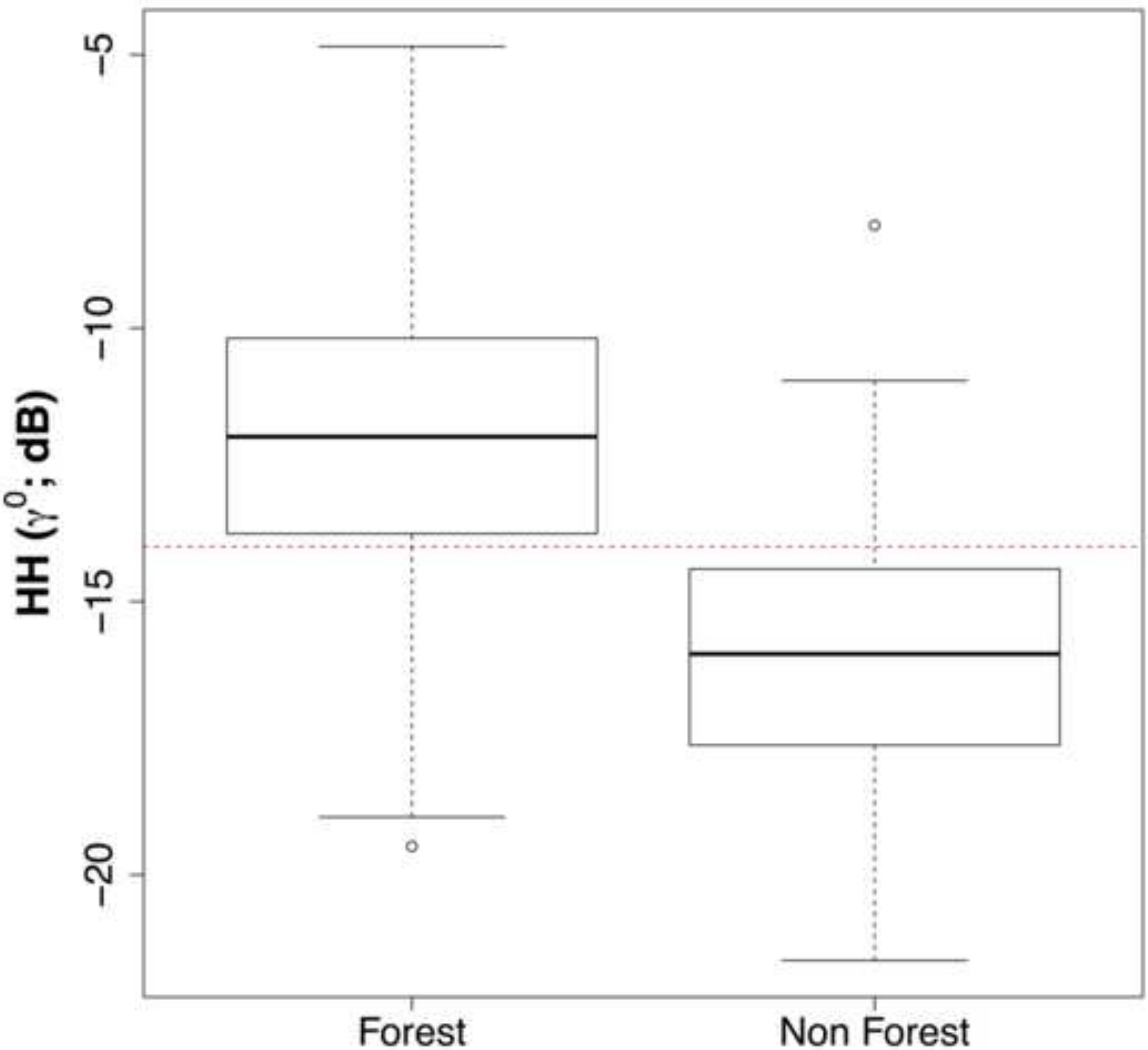

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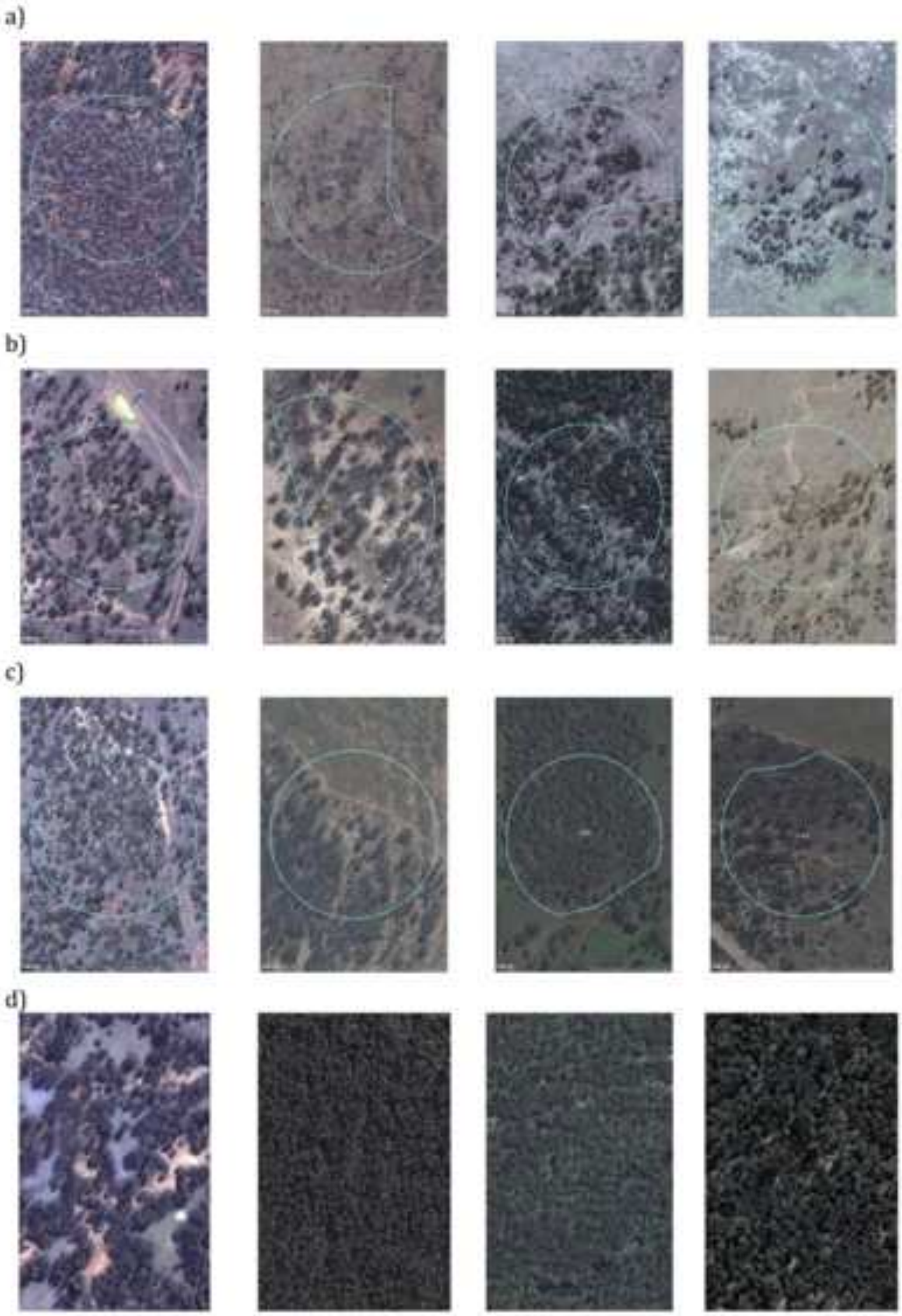

Figure 5

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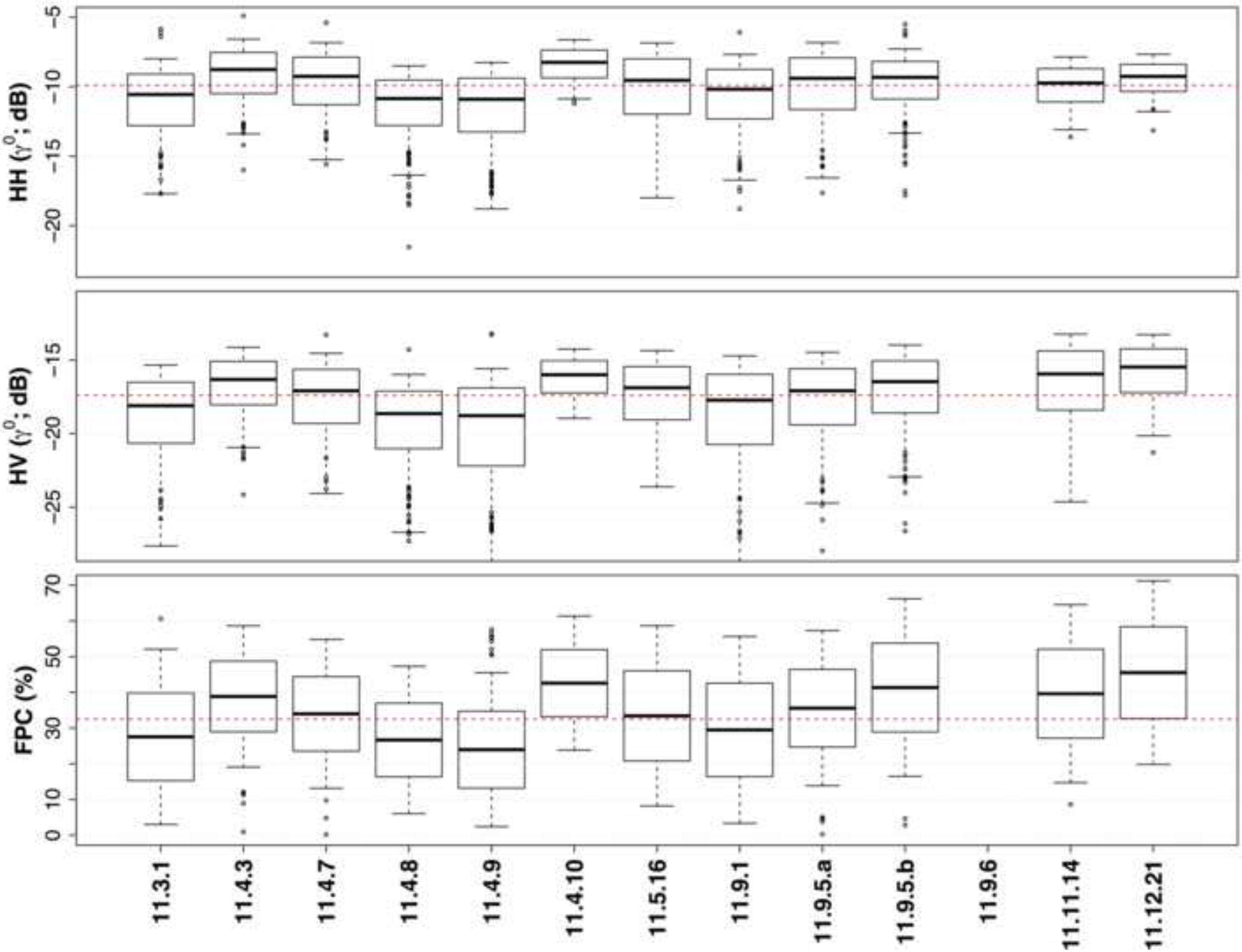

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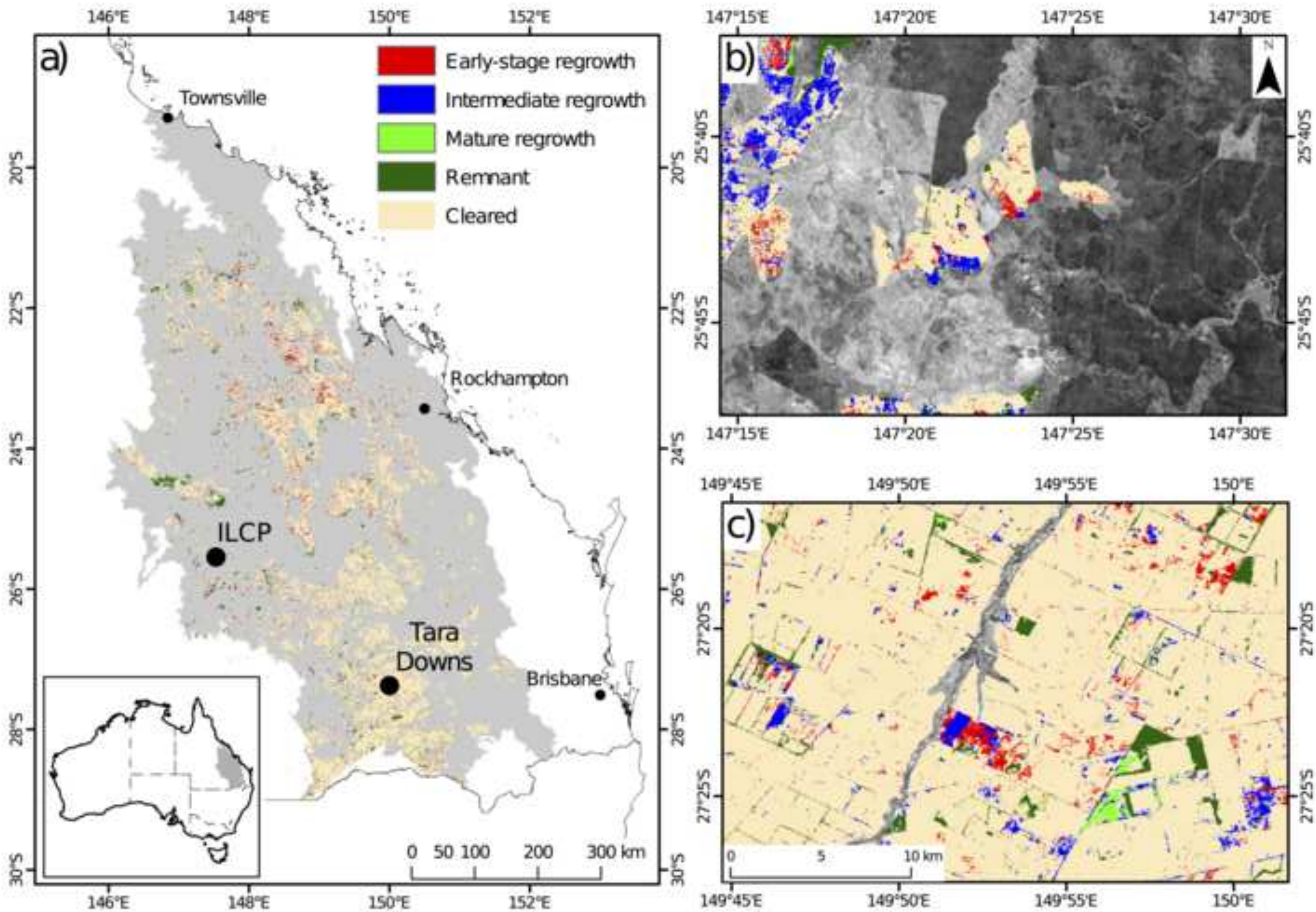

Figure 7
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